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In reply refer to: E-25-6AF

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Subject: Final Report
Project Director(s): Sadowski, Dennis
Telephone No.: 404-385-1686
Contract No.: AGR DTD 11/4/02
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"FORCED INTERNAL CONVECTION MIST COOLING HEAT TRANSFER'

The subject report is forwarded in conformance with the contract/grant specifications.

Should you have any questions or comments regarding this report(s), please contact the Project Director.

Sincerely,

Final Report

Forced Internal Convection Mist Cooling Heat Transfer

Contract #: AGR DTD 11/4/02

Project Number E-25-6AF

September 26, 2013

Submitted to

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Submitted by

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I. SUMMARY

This report describes work completed and results achieved on the" Forced Internal Convection Mist Cooling Heat Transfer" project from its inception on November 4, 2002 through its conclusion on August 31, 2013. This work involved close collaboration between the Georgia Institute of Technology (GT), the Schoonover Consulting Group (SCG), and the Naval Research Laboratory (NRL). The primary goal of the project was to design, develop, and test a system to adequately cool the Hibachi foils in the Electra KrF laser at the Naval Research Laboratory in Washington, DC.

Though it took several iterations, we did successfully devise a system which met the goal of keeping the foils cool with minimal disruption to the focal profile or efficiency of the laser. By withdrawing a relatively small amount of KrF gas from the laser and redirecting it towards the Hibachi foils in the form of hundreds of tiny high velocity near-wall jets the foils showed a dramatic decrease in temperature. Focal profile measurements of the laser beam were far better than that achieved by any other cooling system. It is unfortunate that Congressional funding cuts scuttled the Electra program before we were able to complete full-scale, long-term testing with gas recirculation.

II. Background

In the Electra laser the Hibachi foil separates the KrF laser gas from the high vacuum required by the cathode which generates the electron beam. When the laser is fired, the electron beam passes through the foil, heating it to a very high temperature. This significantly weakens the foil and may lead to a rapid catastrophic failure which could damage many components within the laser.

Prior to the involvement of Georgia Tech and SCG, the NRL tried several methods to cool the foils by forced convection. This included running the KrF gas through the lasing chamber and high velocity and using reciprocating louvers to momentarily redirect the gas flow towards the foils at the moment of firing of the electron beam. Both methods severely disrupted the focal profile of the beam and neither provided adequate cooling to the foil.

The original proposal by SCG and GT was to add a second foil adjacent to the first and injecting a fine mist of water between the foils. This idea was developed and tested between 2002 and 2006, first using a smaller lab-scale test apparatus before culminating in a full-scale test on Electra in 2006. The concept worked very well in that the foils were kept cool and there was no perturbation of the focal profile even at high rep rates. However, this system markedly reduced the e-beam transmission and required a substantial amount of power to create and inject the mist. There was also the danger of leakage of water into the laser, which could potentially damage the cathode, optics, and vacuum pumps. It was deemed that the parasitic losses and the potential risks were too great to incorporate this system, so we were asked to look into alternative cooling methods.

Our second proposal was to create a high velocity gas curtain which would hug the foil and cool it by forced convection. The concept is similar to the forced convection scheme provided by the louvers, but without the mechanical complications of so many moving parts. Also, the gas curtain could be controlled independently of the bulk gas flow in the lasing chamber. A lab-scale adjustable air knife was built in 2007 and testing done at GT to examine air curtain behavior adjacent to a flat surface. Initial results looked promising, so a full-scale apparatus was quickly built and tested on Electra in the summer of 2007. While the gas curtain cooled the bottom of the foil, it dissipated too rapidly to adequately cool the upper portion of the foil, resulting in unacceptably high temperatures.

The third iteration for foil cooling, which started in 2007, was the “vertical headers/horizontal jets” concept which as in the second proposal drew off a small amount of the KrF gas from the bulk flow and redirected it towards the foil. However, this time a series of vertical header tubes were placed behind the Hibachi ribs and fed from manifolds mounted above and below the Hibachi frame. Each header tube had 51 small holes in a staggered pattern from which gas jets would issue towards the foil. A pair of vertical header tubes would cover the foil area between adjacent Hibachi ribs. The ribs, being water cooled, shielded the header tubes and also cooled the edges of the foil by conduction. The tubes were mounted against the ribs, placing the jets very close to the foil surface. An electrically heated foil strip which simulated the foil between a pair of Hibachi ribs was extensively tested in the GT lab to determine optimal jet speed, angle of attack, and foil proximity to maximize cooling and coverage. Thermal imaging showed the concept worked very well, so a full-scale apparatus was built and tested on Electra at NRL in April 2008.

Initial testing at NRL was done in a once-through mode, that is, the headers were fed from external tanks as a quick proof of concept experiment. The results were excellent, so plans were made to come back to NRL to install a recirculation loop to allow for long duration runs. However, at this time NRL began experimenting with a new “scalloped” Hibachi design and further testing of the vertical headers concept was put on hold until sealing issues with the scalloped Hibachi were resolved by NRL. In the scalloped Hibachi design the ribs were moved inwards from the frame, so the test apparatus we had built for the non-scalloped Hibachi did not work as well since the jets were much farther from the foil than previously. We were in the process of modifying our apparatus when Congressional budget cuts severely curtailed work on the Electra program for several years. Georgia Tech requested and received several no-cost extensions in the hope that the program would be revived. However, this does not appear to be feasible in the near term, and with the Principal Investigator leaving Georgia Tech the Institute’s involvement with the Electra program will end.

III. Discussion

As SCG and GT worked very closely on this project, detailed reports of all work done were written jointly and submitted to the NRL. There is no need to rehash all the work done at GT and the results achieved over the 11 year span of this project, but the key achievements are:

1. The vertical headers cool the foil as effectively as the V-plate, but allow the recirculator to be run at a much lower power consumption level.
2. When cooling the foil with vertical headers, the beam focal profile is excellent. It is far better than when the V-plate or other cooling methods are used.
3. The vertical headers provided very uniform cooling of the entire foil. There was very little evidence of hot spots or general foil discoloration.

In addition to meeting the technical goals of the project, this research served as the basis for the thesis work for two PhD students, Vladimir Novak and Bo Lu. At least nine articles based on this work were published in scientific and engineering journals, and Dr. Lu continues to submit manuscripts for additional publications. This work was presented at no less than five major conferences on fusion energy.

IV. Conclusions

We have demonstrated both in the laboratory and on Electra itself that the vertical header jet cooling concept works quite well in keeping the transmission foils cool even at high rep rates. In addition, this method appears to have minimal impact on the focal profile of the laser beam. If Congress chooses to re-establish funding to the program, additional tests using closed-loop recirculation of the laser gas may be tried. We expect a high probability of success if this should occur.